Research on the Application Method of Millimeter Wave Radar in Bridge Deflection Measurement

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RESEARCH ON THE APPLICATION METHOD OF MILLIMETER WAVE RADAR IN BRIDGE DEFLECTION MEASUREMENT

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Abstract: Millimeter-wave radar is a new type of equipment that has been applied in bridge deflection health monitoring in recent years，with the advantages of all-weather, low power consumption, non-contact and high precision. In this paper, based on the background of Suzhou Wujiang East Taihu Bridge, based on theoretical analysis and optimization function construction, an error reduction method of millimeter-wave radar applied to bridges across rivers and lakes is proposed. At the same time, the experimental verification is carried out according to the bridge load experiment and health monitoring, and the comparative analysis shows that this method can effectively improve the measurement accuracy, which provides theoretical support and reference for the application of millimeter-wave radar in the health monitoring of bridges across rivers and lakes.

Keywords: Millimeter wave radar; deflection monitoring; optimization function construction; error correction.

1 Introduction

The bridge health monitoring system began in the 80s of the 20th century, initially tried to use by the United States, Britain, etc. The Jiangyin Yangtze River Bridge, which opened to traffic in 1999, is one of the earliest bridges in China to install a health monitoring system. With the rapid development of network technology, the monitoring system has gradually achieved the goals of real-time monitoring, synchronous analysis and data sharing [1]. The indexes measured by the bridge health monitoring system mainly include displacement, deformation, crack, temperature, wind speed, acceleration and so on. Deformation, crack, temperature, wind speed, acceleration and other indicators have been mature and accurate measurement methods, but the displacement monitoring has not found a suitable method.

The vertical displacement of the main beam is called deflection, which is an important parameter to determine the stiffness and bearing capacity of the bridge [2], and also an important basis for evaluating the health status of the structure [3]. Accurate monitoring of girder deflection is of great significance for the evaluation of bridge health and structural safety [4]. At present, bridge deflection measurement methods are mainly divided into contact and non-contact: (1) Contact deflection measurement methods include mechanical instruments (dial indicator, dial indicator, deflection meter, etc) and guyed displacement meters This kind of instrument has the characteristics of fast, stable and high precision, but it needs to set up the support at the fixed point, which is only suitable for the measurement when the bridge clearance is not high and it is convenient to set up the support [5-6]. (2) Non-contact deflection measurement methods mainly include optical instruments, connecting tubes, electromagnetic wave equipment, etc. Optical instruments have the advantages of automatic and real-time, but they are greatly restricted by environmental factors. Atmospheric turbulence and river lake surface will cause beam jitter to affect the measurement accuracy. The deflection test principle of the liquid connecting pipe is simple, which can realize automatic measurement and the measurement process is not easily affected by the environment. However, the liquid response frequency in the connecting pipe is limited, which can only be used for low-frequency bridge static deflection measurement, and can not be used for bridge dynamic high-precision deflection measurement [7-8]. Compared with the above methods, the millimeter-wave radar based on the principle of electromagnetic wave has obvious advantages in measuring deflection: 1) it can achieve a wider frequency modulation bandwidth of the transmitted signal and has a high range resolution [9]; 2) it can simultaneously detect the speed and distance of multiple targets, and can continuously track the target ; 3) it has the advantages of all-weather, low power consumption, non-contact, high precision and high efficiency [10]. In recent years, millimeter wave radar has been used in many projects, and many scholars have also studied its monitoring methods and effects [11-15]. It can be seen from the above research that millimeter wave radar has obvious advantages in deformation and acceleration monitoring, but cannot achieve high accuracy in deflection monitoring because of the harsh on-site environment of the bridge. In order to solve the accuracy problem of displacement monitoring, based on the measurement principle of millimeter wave radar, this paper constructed an optimization function and combined detection means with monitoring, which realized the effect of high-precision displacement monitoring of millimeter wave radar.

2 Measurement Principle of Millimeter Wave Radar

Millimeter wave radar transmits electromagnetic waves that are not susceptible to environmental interference. Radar is divided into transmitter, reflector and receiver. The distance change from the transmitter to the reflector can be calculated by multiple transmission and reception of the radar signal. In recent years, based on this feature of millimeter wave radar, it has been used for deflection measurement of bridge structures [11]. The basic principle of measurement is shown in Fig. 1.

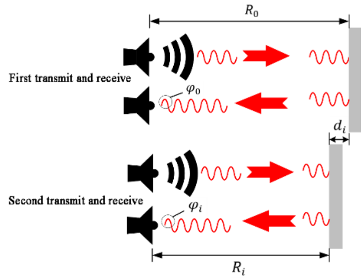

Fig. 1. Radar test phase change diagram

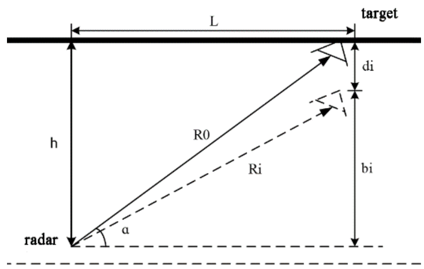

Fig. 2. Diagram of measuring bridge deflection by millimeter wave radar

Millimeter-wave radar transmits electromagnetic waves to the target point and is reflected back. Through continuous emission and reflection, a series of changing phases are obtained. Through these changing phases, the vibration displacement of the target point can be calculated as shown in Eq. (1):

$$\varphi_i = \frac{4\pi}{\lambda} R_i \tag{1}$$

In which λ is the operating wavelength of radar; R_i is the distance between radar and observation point; φ_i is the interference phase in measurement

3 Bridge Deflection Measurement Method Based on Millimeter Wave Radar Technology

The principle of millimeter wave radar applied to the field of bridge deflection measurement is shown in Fig. 2 .

In Fig. 2, R_0 is the distance between the radar and the observation point after the equipment is installed; R_i is the distance between the radar and the observation point after the bridge is deflected; h is the vertical height of the observation point from the radar, d_i is the bridge deflection value, L is the horizontal distance between the radar and the section where the target is located, b_i is the vertical distance between the radar and the target after the vehicle is loaded, and i is the measurement times.

Since d_i is much smaller than h, Eq. (3) and Eq. (4) can be established according to Fig. 2 :

$$R_i = R_0 - d_i sin\alpha \tag{3}$$

$$sin\alpha = \frac{h}{R_0} \tag{4}$$

And the interference phase between the i-th measurement and the initial distance is:

$$\varphi = \varphi_i - \varphi_0 = \frac{4\pi}{\lambda} d_i sin\alpha = \frac{4\pi}{\lambda} d_i \frac{h}{R_0} \tag{5}$$

The bridge deflection d_i can be expressed as shown in Eq. (6) [13]:

$$d_i = \frac{\lambda R_0}{4\pi h} (\varphi_i - \varphi_0) \tag{6}$$

However, the test results in actual use do not match expectations. The main reasons affecting the measurement accuracy are analyzed as follows.According to Eq. (3), the bridge deflection d_i in the measurement process is

$$d_i = \frac{R_0 - R_i}{sin\alpha} \tag{7}$$

The parameters h and R_0 in the Eq. (7) are measured, and there is some errors in measurement. The bridge is usually in a relatively harsh environment, and the radar measurement accuracy will also decrease due to the wind load. Usually, the millimeter wave radar is set at the bridge pier when measuring the deflection, and the target is set at the test section. When the bridge span is larger, the parameter $sin\alpha$ is smaller, which makes the radar measurement errors amplified. It is found that when R_0 = 50m and h = 7m, the variation of radar measurement value $(R_0 - R_i)$ reaches 0.5mm, which will lead to the final deflection error of about 3.6mm. This accuracy cannot meet the measurement requirements of bridge deflection.

Therefore, aiming at the measurement characteristics of millimeter wave radar and the measurement accuracy requirements of bridge deflection, an optimization function is constructed to optimize the method of monitoring bridge deflection by millimeter wave radar.

4 Deflection Measurement Method Based on Optimization Function

In order to construct accurate optimization function parameters, based on the test principle described in the previous section, the initial parameter test of bridge load test is added, which are parameter L and parameter b_i respectively.

In the load test, millimeter wave radar is used to monitor the deflection, and high precision total station is used to check synchronously. Taking the measured deflection value of total station as the known parameter, the known parameters in Fig. 2 are R_0, R_i and d_i, and the unknown parameters are L_i and b_i. The Eq (7) and Eq (8) are established according to the geometric principle :

$$b_i = \frac{R_0^2 - R_i^2 - d_i^2}{2d_i} \tag{7}$$

$$L_i = \sqrt{R_i^2 - \frac{(R_0^2 - R_i^2 - d_i^2)^2}{4d_i^2}} \tag{8}$$

After calculation, the measured value of millimeter wave radar after deflection measurement and the value of each parameter obtained by conversion can be obtained. Usually, when measuring the deflection, the section to be measured will be measured many times. Theoretically, the horizontal distance L between the radar and the target remains unchanged under the loading of the same section at all levels. However, due to the error between the radar and the total station in the measurement process, the L_i values obtained by loading at all levels are different in practice.

The method of transforming a problem into an optimization framework by constructing an objective function is widely used in the field of computer. The optimization problem can be summarized as the mathematical problem shown in Eq. (9).

$$minf(x), x\epsilon X \tag{9}$$

Taking the linear fitting of two-dimensional data as an example, the linear fitting of two-dimensional data considers some points on the two-dimensional plane, and solves an optimal linear function to describe the correspondence between the horizontal and vertical coordinates of these points. The two-dimensional data points are denoted by (x_i, y_i), $i = 1,..., n$. Without considering the linear function parallel to the coordinate axis, the equation can be assumed to be $y = ax+b$, as shown in Eq. (10):

$$Y = (y_1, \dots, y_n)^T, A = (a, b)^T \tag{10}$$

The fitting problem can be summarized as the optimization problem shown in Eq. (11) :

$$min(Y - XA)^T(Y - XA) \tag{11}$$

In practical engineering optimization design problems, there are generally different constraints. Constrained optimization problems can be written as follows[17]:

$$MinF(x) \tag{12}$$

$$a_i \le x_i \le b_i \tag{13}$$

In which X=$x_1, x_2, \cdots, (x_n \in R^n)$ is the n-dimensional vector; F(x) is the objective function; $g_m(x)$ is a constraint function with m constraints. Aiming at the deflection measurement using millimeter wave radar, the calculated deflection value d_i' under the other levels of loading can be obtained after the L_i value under a certain level of loading is obtained by using Eq. (8), as shown in Eq. (14):

$$d_i' = \sqrt{R_0^2 - L_i^2} - \sqrt{R_i^2 - L_i^2} \tag{14}$$

After obtaining the calculated deflection value d_i' under each loading level, the optimization function is constructed with the parameter L as the independent variable, the maximum and minimum values of L_i under n-level loading as the constraint conditions, and the sum of squares of the calculated deflection and the measured deflection difference of the total station under n-level loading as the objective function, as shown in Eq.(15) to Eq.(17) :

$$min \sum_{i=1}^{n} (d_i - d_i')^2 \tag{15}$$

$$d_i' = \sqrt{R_0^2 - L_m^2} - \sqrt{R_i^2 - L_m^2} \tag{16}$$

$$L_{min} \leq L \leq L_{max} \tag{17}$$

In Eq.(16), m is all loading cases when $m \neq i$. After obtaining the optimal solution of the parameter L, the deflection d_i is shown in Eq. (18) :

$$d_i = \sqrt{R_0^2 - L^2} - \sqrt{R_i^2 - L^2} \tag{18}$$

5 Engineering Example Analysis

5.1 Engineering Background

There is a prestressed concrete continuous box-girder bridge in an economic development zone in Suzhou, Jiangsu Province. The span is 70m + 110m + 70m. The main beam is a large cantilever variable cross-section single-box three-cell prestressed concrete box girder. The bridge facade is shown in Fig. 3, and the cross section is shown in Fig. 4.

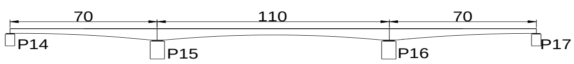

Fig. 3. Bridge facade diagram

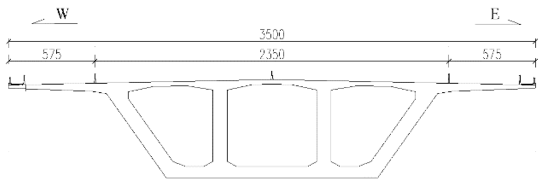

Fig. 4. Bridge cross section diagram

5.2 Deflection Monitoring System Layout

Since the design load of the bridge is controlled by the most unfavorable conditions, considering the uncertainty and randomness of the bridge operating load [18-19], the test conditions of the mid-span cross-section (Section A) and the 1/4 cross-section (Section B) are analyzed as shown in Fig. 5.

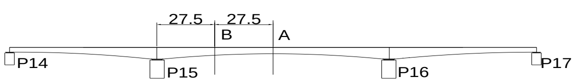

Fig. 5. Test cross section of load test

According to the characteristics of the bridge, the position of measuring points is shown in Fig. 6, and the site layout is shown in Fig. 7:

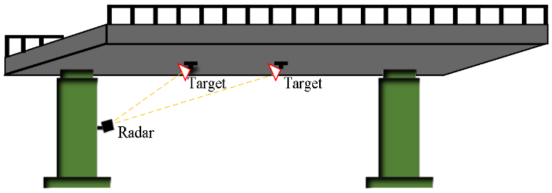

Fig. 6. the Position of Millimeter Wave Radar

(a) The Target of Deflection Monitoring (b) The Radar of Deflection Monitoring

Fig. 7. The Actual Layout Location of Millimeter Wave Radar

5.3 Millimeter Wave Radar Deflection Measurement Data Analysis

Through the millimeter wave radar deflection measurement principle described in the first section, the bridge deflection d can be calculated. The measured deflection values of the mid-span cross-section (Section A) and the 1/4 cross-section (Section B) obtained by millimeter wave radar and total station are shown in Table 1:

Table 1. Comparison of deflection values from millimeter wave radar and total station.

Test section	Load level	Theoretical value /mm	Measured values of radar /mm	Measured values of total station /mm	Error/ %
Section A	One-level loading	8.5	5.8	7.5	-22.7
	Two-level loading	12.2	6.8	10.5	-35.2
	Three-level loading	26.5	11.2	20.1	-44.3
	Four-level loading	39.8	14.5	27.9	-48.0
Section B	One-level loading	5.7	4.2	5.0	-16.0
	Two-level loading	7.5	5.5	6.8	-19.1
	Three-level loading	12.8	8.3	10.7	-22.4
	Four-level loading	18.5	10.6	14.8	-28.4

By comparing the measured data of radar and total station under the four different load levels in Table 1, it can be found that: 1) As the load level increases, the error between the measured value of the radar and the total station also increases, and the error under the four-level loading of the section A reaches -48.0 %. At the same time, the error of the section A at all levels of loading is also greater than the error of the section B. The horizontal distance between the section A and the radar installation cross-section is about 50 meters, while the horizontal distance between the section B and the radar installation cross-section is about 25 meters. The distance gap is the root cause of the increase in error; 2) The errors of section A and section B under four-stage loading are large, which is mainly due to the error between the parameters R_0 and h in Eq. (4). Due to the characteristics of radar and its own equipment, as the distance increases, the measurement accuracy of radar will be reduced. In this test, the distance R_0 between the millimeter wave radar and the target reaches 50 meters, and the height h between the test point and the radar reaches more than 7 meters. Due to the restriction of the field environmental factors, it is almost impossible to control the error of the parameter $sin\alpha$ to 0.01, which is also the root cause of the error of section A in the four-level loading reaching -48%.

5.4 Application of Deflection Measurement Based on Optimization Function Construction

After calculation, the parameters obtained by the conversion of the measured values of the millimeter wave radar under the load of the middle span and the 1 / 4 section of the middle span are shown in Table 2. The parameter v0 in the table is obtained by constructing an optimization function after three-stage loading.

After calculation, the parameters of the millimeter wave radar measured values of section A and section B under load can be obtained, as shown in Table 2. The parameter L_0 in the table is obtained by constructing an optimization function after three-stage loading.

Table 2. The calculation table of radar measured value (unit : mm).

		One-level loading	Two-level loading	Three-level loading	Four-level loading
Section A	R_i	52970.88	52970.45	52969.90	52969.22
	L_i	52861.73	52860.51	52863.44	52864.21
	L_0	52862.81			
Section B	R_i	25667.55	25667.09	25666.67	25666.02
	L_i	25492.83	25491.48	25492.51	25495.85
	L_0	25493.96			

It can be seen from Table 2 that the horizontal distance L_0 between the vertical section of the millimeter-wave radar located in section A and the vertical section of the target is about 52.9m, and the horizontal distance L_0 between the vertical section of the millimeter-wave radar located in section B and the vertical section of the target is about 25.5m, which is approximately the same as the position of the radar and the target installed in the scheme. This value can be used as the basis for the deflection calculation of Eq. (18).

According to the Eq. (15) to Eq. (17), it can be seen that the value of L can be obtained by constructing the optimization function equation for each level of loading under multi-level loading. The minimum value of the sum of squares obtained by Eq. (15) is taken as the vertical coordinate, and the minimum value L under the four-level loading is substituted into the ten working condition values of the health monitoring stage for solution. The results are shown in Fig. 8 :

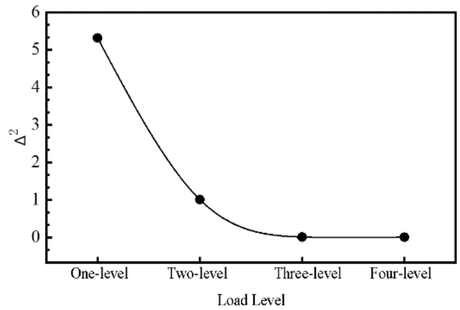

Fig. 8. Four level loading accuracy verification diagram.

The vertical coordinate Δ^2 in Fig. 8 is the sum of squares of the difference between the measured values of radar and total station obtained by Eq. (18) when five times of loading are randomly performed. The smaller Δ^2 indicates the higher accuracy of the *v* value obtained by the optimization function structure under the first n-level loading. According to Fig. 8, it can be seen that the inflection point appears at the three-level loading, indicating that the accuracy of the *v* value obtained by using the first three-level loading to construct the optimization function has reached the bottleneck. Although the accuracy is still improved after using the first four-level loading to construct the optimization function, the improvement is very limited. Considering the time cost and economic cost in practical engineering, it is not necessary to carry out four-level and above four-level loading to construct the optimization function to solve the parameter *L*. Therefore, when using the optimization function construction method for error correction, it is recommended to carry out three-level loading on the bridge.

In order to verify the effectiveness of the correction method, another load is used for loading, and the total station is used for deflection measurement as an accurate value for verification. As shown in table 3 :

Table 3. Modified deflection error table.

	Before correction /mm	After correction /mm	Exact value /mm	Pre-correction error /%	Error after correction /%
Section A	17.5	29.2	30.5	-42.6	-4.3
Section B	12.8	16.7	17.6	-27.3	-5.1

It can be seen from Table 3 that the deflection error is effectively reduced after the correction by using the above method, which has important reference value and significance for the deflection analysis of the East Taihu Lake Bridge after entering the bridge operation state.

After the bridge enters the operation stage, the millimeter wave radar is used to monitor the deflection index health. After the error correction, the monitoring value is shown in Fig. 7 :

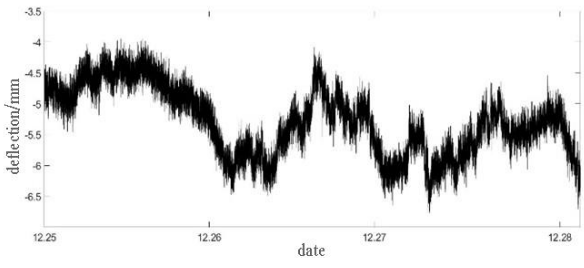

Fig. 9. Bridge deflection health monitoring value.

At 12: 00 noon on December 26,2021, the total station was used to measure the deflection as an accurate value. The comparison of the deflection values before and after correction with the millimeter wave radar data is shown in Table 4.

Table 4. The comparison table of total station and radar measured value.

Before correction /mm	After correction /mm	Exact value /mm	Pre-correction error /%	Error after correction /%
2.84	3.86	4.05	-29.9	-4.7

It can be seen from Table 4 that after using the deflection measurement method based on the optimization function, the measured deflection value of the radar is obviously close to the measured value of the total station, which verifies the effectiveness of the error correction method described in this paper.

6 Conclusions

Aiming at the problem of bridge deflection monitoring, this paper uses millimeter wave radar to monitor, constructs optimization function to improve the measurement accuracy, and draws the following conclusions :

(1) Millimeter wave radar can be used for deflection monitoring of medium and small span bridges. When the test distance is within 30 meters, the measurement accuracy can reach about 95 %. When the measurement distance exceeds 50m, the deflection measurement accuracy drops to about 90 %, which cannot meet the needs of bridge health monitoring.

(2) The measurement accuracy of horizontal distance between millimeter wave radar and target is the key factor to determine the accuracy of deflection measurement.

(3) After using the optimization method based on the optimization function structure proposed in this paper to correct the measured value of millimeter wave radar deflection, the measured accuracy of bridge deflection can be significantly improved, and the maximum error rate can be reduced by 90 % and controlled at about 5 %.

Acknowledgement

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